

A Phenomenological Approach for Condition Monitoring of Magnetic Cores based on the Hysteresis Phenomenon

Hamed Hamzehbahmani, *Senior member, IEEE*

Department of Engineering, Durham University, Durham, DH1 3LE, UK

Abstract- Hysteresis phenomenon is a distinctive approach to describe natural behaviour of the magnetic materials and magnetic cores. This paper proposes a phenomenological approach for core quality assessment and condition monitoring of magnetic cores with grain-oriented electrical steels. The developed technique is based on the hysteresis phenomenon and interpreting the most distinctive parameters of the measured dynamic hysteresis loops. In this study, artificial short circuits were introduced between the laminations of stacks of two, three and four Epstein size strips of Fe-3 wt % Si grain oriented steel. The results showed that, condition monitoring of the magnetic cores can be effectively performed by measuring and analysing the hysteresis loops.

Index Terms: Condition monitoring, transformer core, hysteresis phenomenon, electrical steel, dynamic hysteresis loop, magnetic loss, relative permeability.

I. INTRODUCTION

Electrical steels are the core material of transformers, rotating machines and other electromagnetic devices. Commercial electrical steels have a silicon content of 3.2 wt % which result in a high resistivity of around $46 \mu\Omega\text{-cm}$. Conventional SiFe electrical steels are produced by cold rolling process, as the most common way of producing electrical steels without cracking. Specific power loss in W/kg or total energy loss in J/m^3 per cycle, and relative permeability are two important factors to characterise electrical steels. Since the first discovery of silicon steel by Robert Hadfield in 1903, the improvement in the magnetic properties of electrical steels has continued almost without stop. In this trend the main emphasis has been on iron loss reduction of the produced materials for high efficiency electromagnetic devices. As the drive for lower power loss electromagnetic devices continues, thin gauge electrical steels have been recognised as a promising technology to reduce magnetic loss. Silicon steel laminations are now commercially available with thicknesses of 0.1 mm up to 0.5 mm gauge [1-2].

In the design and manufacturing phase of the magnetic cores, electrical steel laminations are processed by different machining tools, e.g. cutting, punching, stamping, welding, etc. Machining processes, however, introduce mechanical and thermal residual stresses, and consequently deteriorate the electric and magnetic properties of the individual laminations [3]. In addition, machining processes may create undesirable edge burr around the cut edges and punched holes. It is well distinguished that edge burr has destructive impacts on quality of the electrical steels and hence the assembled magnetic cores. Electrical

contact with low resistance and hence inter-laminar fault (ILF) between the adjacent laminations have been identified as major consequences of edge burr [4-9]. ILFs problem could also arise during the operation of the devices due to a number of reasons, e.g., vibration of loose strips or windings, arcing from winding failure, mechanical stress due to electrical short circuits, tensional/compressional stress during transportation or earthquakes in earthquake-prone regions [7-11].

ILFs could create fault current loops in the magnetic cores and result in circulating eddy currents between the shorted laminations. Considering the relatively small dimensions of ILFs, e.g. those caused by edge burrs, usually high eddy current densities occur at the shored points, which contribute in high local power loss and local hot spot in the defective zones of the core [11-12]. With a few faults, the induced fault currents may not be very high to impact the overall performance of the device, specifically in large transformers and electrical machines [11-13]. These types of faults may not even be detected using the commercial core quality assessment methods, but they could contribute to a remarkable amount of energy loss throughout the lifetime of the device. Importance of ILF problem and condition monitoring of the magnetic cores is admitted by the designers and users of all types of electromagnetic devices with laminated core. Therefore, it is widely acknowledged that core quality assessment to identify any ILFs should be performed at an early stage before they progress to machine failure. Perspective view of a three-phase transformer core with three possible ILFs on the limbs and yoke is shown in Fig 1. An example of core failure caused by ILF in a three-phase 535 MVA, 230 kV/22 kV, Y/ Δ , 60 Hz power transformer is shown in Fig 2.

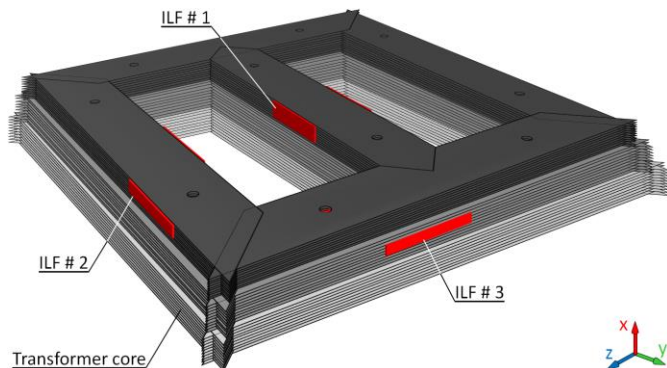


Fig 1 A three-phase three-limb transformer core with ILF in the limbs and yoke



(a)



(b)

Fig 2 Core failure in a 535 MVA three phase power transformer caused by ILF

Core quality assessment and condition monitoring of the magnetic cores have been an active research field and engaging topic for electrical steel manufacturers, and designers of the magnetic cores. During the last few decades, analytical and experimental approaches have been developed and effectively employed to study impacts of ILFs on performance of magnetic cores of power transformers [14-17] and rotating machines [18-22]. Most of these work, however, are focused on measuring the localised power loss and temperature, as well as on the overall power loss of the magnetic cores.

In this paper, impacts of the ILF on the hysteresis behaviour and magnetising process of the magnetic cores are studied. The investigations were carried out on stacks of two, three and four Epstein size strips of conventional grain-oriented (CGO) silicon steel subjected to artificial ILFs. These studies were performed based on the measured dynamic hysteresis loop (DHL) of the test samples. As a new approach in this field, effects of ILFs on

shape of the hysteresis loops, and two distinctive quantities of the hysteresis loops, coercive field H_c and residual magnetic field B_r , were investigated. Furthermore, impact of each artificial fault on the relative magnetic permeability of the test samples, as an important quality indicator of the material, was studied. The results of this work give a new insight to better understanding the impacts of ILFs on hysteresis behaviour of the magnetic cores, to improve performance of the transformers and electrical machines. This will increase the previous knowledge on core quality assessment and condition monitoring of the electromagnetic devices.

II. THEORETICAL BACKGROUND

According to the general theory of hysteresis, a phase lag between input and output signals, naturally, results in hysteresis loop. In electromagnetism, hysteresis phenomenon has an important concept to characterise magnetic materials under different magnetising conditions. Despite the complex nature of the magnetic hysteresis, it contains useful information about the intrinsic properties of the materials, their behaviour and response to different magnetisation regimes. Therefore, the comprehension of the hysteresis phenomenon is a reliable and adequate tool to characterise any sort of magnetic material.

Hysteresis loops may take many different shapes, however without going through the details of their shapes, they can be characterised by some distinctive parameters. Two quantities of the hysteresis loops, with significant importance, are coercive field H_c and residual magnetic field B_r . Magnetic materials can be classified based on these quantities, and other related parameters [23]. In addition, relative permeability μ_r and total energy loss W_{tot} can be determined based on the hysteresis loops. Accurate measurements or modelling of hysteresis loops can provide these quantities for any given material.

A. Relative permeability

Relative permeability of the magnetic materials, at a particular flux density and magnetising frequency, is determined based on the peak flux density B_m and peak magnetic field strength H_m for one magnetising cycle. In principle, flux density $B(t)$ and magnetic field strength $H(t)$ cannot reach the maximum values at the same instant, due to the dynamic loss components, mainly at low flux densities or high frequencies [23-24]. Therefore, during one magnetising cycle, two salient magnetic field strengths with different concepts can be defined: H_m , peak magnetic field strength; and H_b , magnetic field strength corresponding to the peak flux density B_m . Two examples of hysteresis loops for GO electrical steel, showing the important quantities, at high flux density and low flux density are shown in Figs 3-a and 3-b, respectively. In Fig 3-a H_m coincides with H_b , while in Fig 3-b H_m differs from H_b .

The relation between the peak flux density B_m and peak magnetic field strength H_m is given by [23]:

$$B_m = \mu_0 \mu_r H_m \quad (1)$$

where μ_0 is permeability of free space and μ_r is relative magnetic permeability of the material. The peak magnetic field strength is given by:

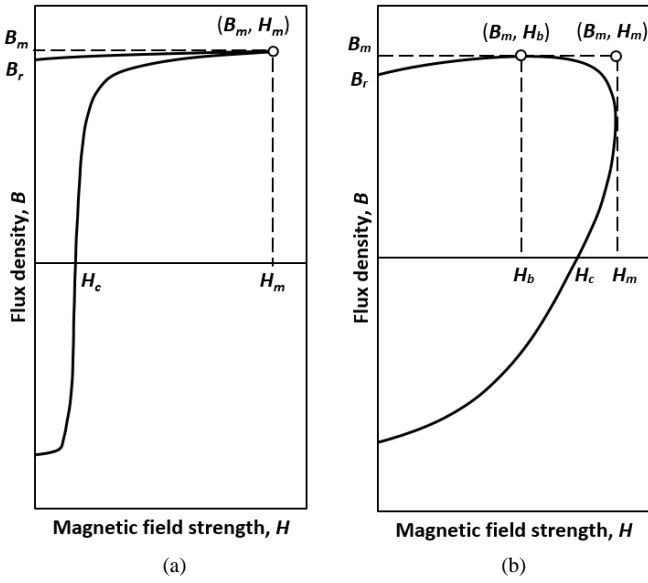


Fig 3 Typical hysteresis loops of GO electrical steel, showing the important quantities, at (a) high flux density and (b) low flux density

$$H_m = \frac{NI_m}{l_m} \quad (2)$$

where N is number of the turns of the magnetising coil, I_m is the peak magnetising current and l_m is the mean magnetic path length of the magnetic circuit. Therefore the effective relative permeability μ_r as a function of flux density is obtained by:

$$\mu_r = \frac{B_m l_m}{\mu_0 NI_m} \quad (3)$$

B. Energy loss and components

The area enclosed by the hysteresis loop measures the total amount of energy loss during one magnetising cycle. This is one of the most important concepts of hysteresis phenomenon and has been used by engineers and physicists to characterise magnetic materials [23]. Thin sheet model (TSM), developed from the principle of statistical energy loss separation, has been identified as a reliable approach to evaluate magnetising processes and energy loss analysis of GO steels. In this approach, total energy loss of the material is expressed by [25]:

$$W_{tot} = W_{hys} + W_{eddy} + W_{exc} \quad (4)$$

where, W_{hys} is hysteresis loss, W_{eddy} is classical eddy current loss and W_{exc} is excess loss component. Energy loss analysis can be carried out based on the static, or quasi-static, and dynamic hysteresis loops, and hence, energy loss separation of (4), can be described by means of magnetic field separation:

$$H(t) = H_{hys}(t) + H_{eddy}(t) + H_{exc}(t) \quad (5)$$

where $H(t)$ is magnetic field strength at the lamination surface, $H_{hys}(t)$ is hysteresis field, $H_{eddy}(t)$ is eddy current field, and $H_{exc}(t)$ is excess field. Using the dynamic models of eddy current and excess fields, (5) yields the well-known TSM [26]:

$$H(t) = H_{hys}(B) + \frac{d^2}{12\rho} \frac{dB}{dt} + g(B)\delta \left| \frac{dB}{dt} \right|^\alpha \quad (6)$$

where $H_{hys}(B)$ is the hysteresis field, d is lamination thickness, ρ is resistivity of the material and δ is directional parameter: $\delta = +1$ for $(dB/dt) > 0$, and $\delta = -1$ for $(dB/dt) < 0$. The exponent α determines the frequency dependence of the excess energy loss component, and $g(B)$ is a function to control shape of the modelled DHL.

Energy loss analysis of GO electrical steels can be also carried out by separating the total energy loss into hysteresis and dynamic loss components. In this method, both classical eddy current and excess fields are integrated into dynamic field, and the TSM for GO steels is expressed as [27]:

$$H(t) = H_{hys}(B) + g_{dyn}(B)\delta \left| \frac{dB}{dt} \right|^{\alpha_{dyn}(B_{pk})} \quad (7)$$

$g_{dyn}(B)$ and $\alpha_{dyn}(B_{pk})$ in (7) differ from $g(B)$ and α in (6). The two component model (7) has demonstrated good accuracy to reproduce DHL of almost all types of GO electrical steels, and hence energy loss analysis [4, 27].

III. EXPERIMENTAL SET-UP AND SAMPLE PREPARATION

Epstein size strips of CGO Fe-3 wt % Si with standard grades of M105-30P and 0.3 mm thick were provided by Cogent Power Ltd. Stacks of two, three and four strips were prepared and labelled as: Pack # 1, stack of two strips; Pack # 2, stack of three strips, and Pack # 3, stack of four strips. Artificial ILFs of $\sim 500 \mu\text{m}$ thick were applied on either side of each pack, using lead-free solder. Top view of one of the test samples with artificial fault is shown in Fig 4, and a perspective view of the test samples is shown in Fig 5.

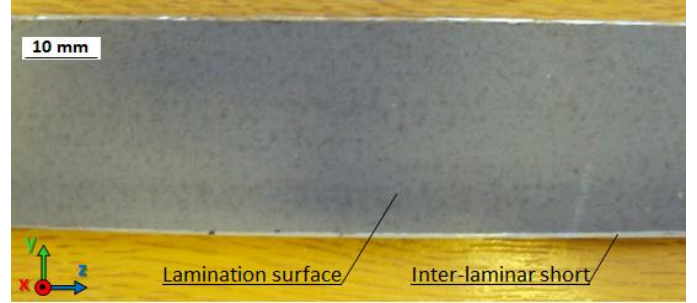


Fig 4 Top view of a test sample with artificial inter-laminar fault

The test samples were magnetised using a standard double yoke single strip tester (SST) under controlled sinusoidal induction at peak flux densities of 1.0 T to 1.7 T, and magnetising frequencies from 50 Hz to 1 kHz. Considering the frequency range of the measurements, two SSTs with different turn ratio were used. For magnetising frequencies from 50 Hz to 400 Hz a low frequency SST with $N_1 = 865$ and $N_2 = 250$ in the primary and secondary windings was used. A high frequency SST with $N_1 = 865$ and $N_2 = 250$ was specifically made for magnetising frequency of 1 kHz, and higher. The magnetising system conforms to the British standard BS EN 10280:2007 [28]. More detail of the experimental set-up can be found in [29].

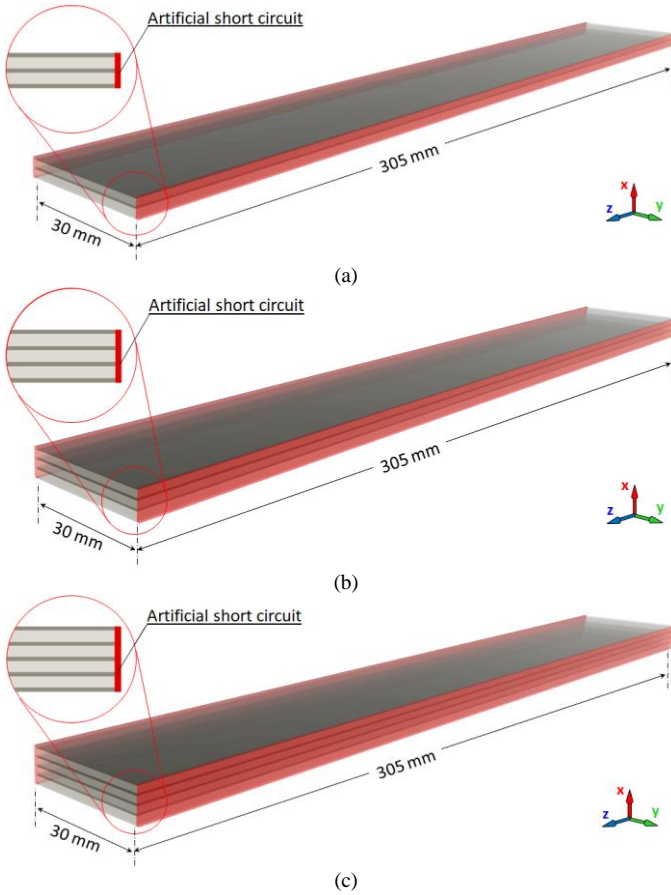


Fig 5 Perspective view of the test samples with artificial faults (a) pack # 1 with two shorted laminations, (b) pack # 2 with three shorted laminations and (c) pack # 3 with four shorted laminations

IV. EXPERIMENTAL RESULTS

Prior to applying the artificial ILFs on the test samples, bulk power loss and DHL of each pack of lamination were measured and recorded separately. Specific power loss and DHL of a single strip (SS), with the same standard grade as the test samples, were also measured; the results were used as reference values to assess the test samples. Bulk power losses of a single strip and the test samples with no artificial ILFs at magnetising frequency of 50 Hz are shown in Table 1. A comparison between the DHLs of a single strip and the test samples, again without artificial ILFs, at magnetising frequency of 50 Hz and peak flux density of 1.7 T is shown in Fig 6.

Table 1 Bulk power loss of a single strip and the test samples prior to applying ILFs at magnetising frequency of 50 Hz

B_{pk} (T)	Bulk power loss (W/kg)				STDEV
	SS	Pack # 1	Pack # 2	Pack # 3	
1.3	0.639	0.640	0.642	0.657	0.009
1.5	0.867	0.870	0.872	0.883	0.007
1.7	1.27	1.28	1.27	1.26	0.006

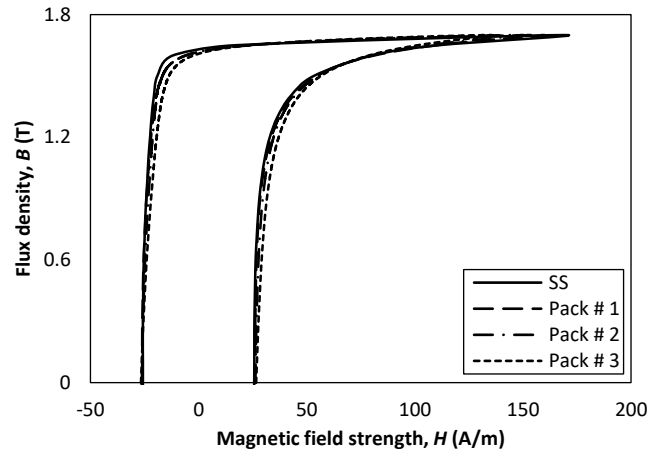


Fig 6 Measured DHL of the test samples before applying artificial ILF at magnetising frequency of 50 Hz and peak flux density of $B_{pk}=1.7$ T

Table 1 shows a negligible variation in the measured power loss of the test samples, with a standard deviation of below 0.01. This implies that total power loss of each pack, with no ILFs, is in close agreement with the specific power loss of the material. This is further supported by the fairly coincidence of the measured DHLs of the test samples, as shown in Fig 6.

A. Bulk power loss measurement

After applying the artificial ILFs, specific power loss of the test samples were measured at peak flux densities of 1.3 T to 1.7 T and magnetising frequencies from 50 Hz to 1 kHz. The results of the measurements that accompany the results of a single strip (SS) are shown in Fig 7. The experiments were run three times at each magnetising point; the results showed a repeatability of better than 0.3 %. Experimental results shown in Fig 7 are the average of three sets of measurements.

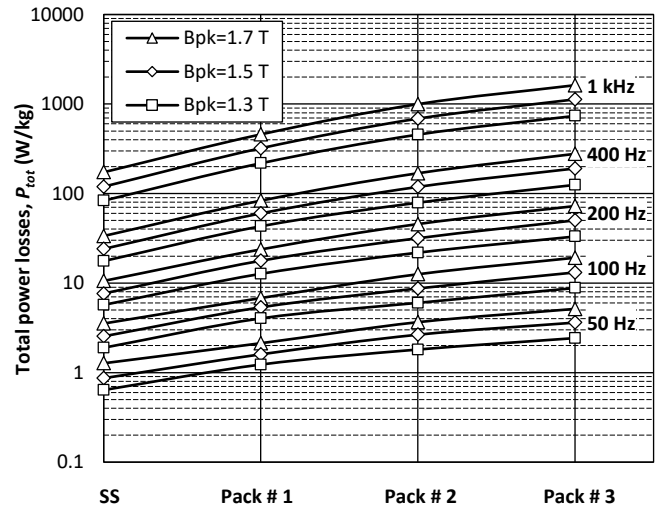


Fig 7 Total power loss of the test samples at different magnetising frequencies and peak flux densities

Fig 7 shows a significant increase in the total power loss of the test samples compare to the specific power loss of a single strip. For example specific loss at $B_{pk} = 1.7$ T and $f = 1$ kHz for a single strip and pack # 3, with four shorted laminations,

increased from 173 W/kg to 1622 W/kg. To highlight the impacts of ILFs on the overall power loss, percentage increase in the bulk power loss of the test samples, compared to the specific loss figure of the material were calculated. The results at peak flux densities of $B_{pk} = 1.3$ T, $B_{pk} = 1.5$ T and $B_{pk} = 1.7$ T are shown in Figs 8-a to 8-c, respectively.

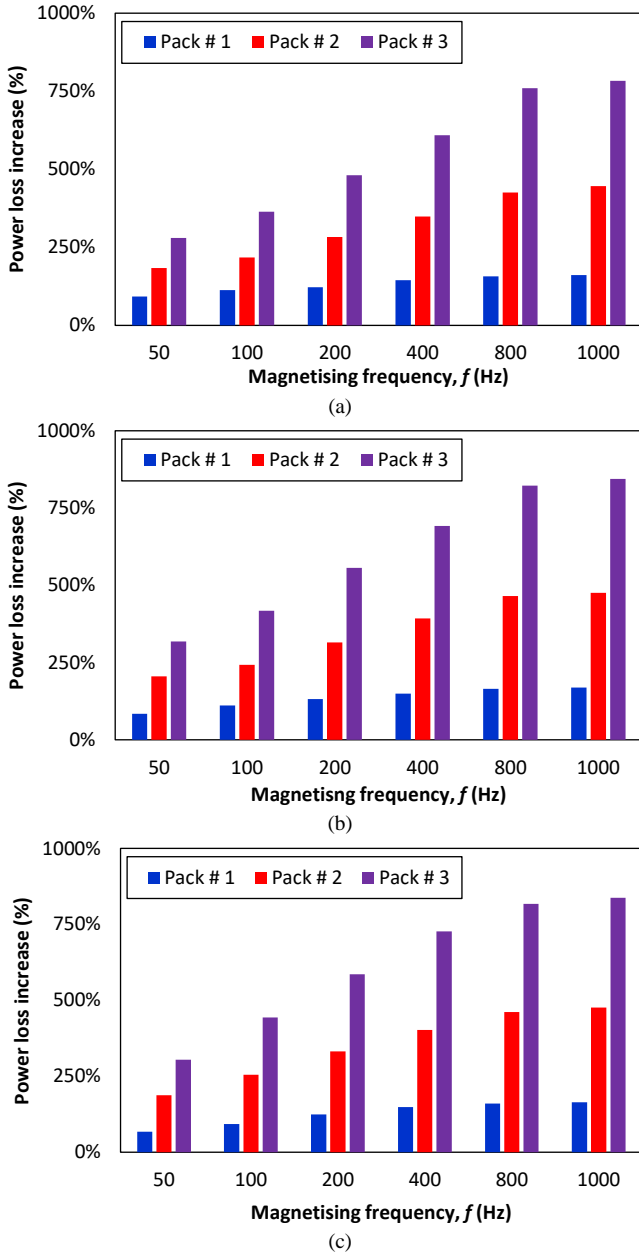


Fig 8 Percentage increase in bulk power loss of the test samples compare to the nominal loss of the material at peak flux densities of (a) $B_{pk}=1.3$ T (b) $B_{pk}=1.5$ T and (c) $B_{pk}=1.7$ T

Fig 8 shows that even for pack # 1, with two shorted laminations, a significant increase of about 92 % in total power loss was occurred at the lowest range of magnetisation, $B_{pk} = 1.3$ T and $f = 50$ Hz. The highest loss increase was observed for pack # 3 at peak flux density of $B_{pk} = 1.7$ T and magnetising frequency of $f = 1$ kHz, which is 840 %.

IEEE std. 62.2-2004 [30] recommends that ILFs which result in 5 % increase in the magnetic loss or hot spots of 10 °C above the ambient temperature, after 2 hours magnetisation, must be considered as serious defects and the magnetic core or the defected zone should be replaced immediately. Recent publications on condition monitoring of magnetic cores show that, even a small number of ILFs has a potential to meet this failure margin, which may eventually lead to machine failure. Identifying these kinds of ILFs depend on many factors including, but not limited to, number of the ILFs, distribution of the fault, axial off-set between the fault points with respect to the magnetising direction, and magnetising conditions [5, 11]. Even though a few shorts between the laminations may not create a high localised power loss and temperature, it could result in a significant amount of energy loss during the lifetime of the machine. In addition to power loss, thermal stress caused by the ILFs could accelerate the degradation of the material coating and results in premature aging of the magnetic core [31]. Therefore, it is extremely important that quality and condition of the magnetic cores to be monitored during the routine tests of the electrical machines, especially for large turbo generators.

Experimental results of Figs 7 and 8 show that, this sort of ILFs could, potentially, lead to machine failure and precautions must be taken to prevent irreversible damage on the core and the machine as a whole. In addition, this test shows that extra power loss increases dramatically by increasing number of the ILFs. In real magnetic cores, the excessive local temperature at the defected zone could damage the insulation coating of the laminations and expand the defected zone. The electromagnetic devices, however, cannot withstand this condition for a long time and if the protection systems do not operate, the fault process will end up in machine breakdown.

B. Hysteresis behaviour of the test samples

Magnetic hysteresis loops may take a variety of different forms which depend on magnetising regime, magnetic and electric properties of the materials, and quality of the cores. Experimental and analytical approaches based on the hysteresis phenomenon have been previously developed by the author for core quality assessment, under sinusoidal [4, 11] and non-sinusoidal excitations [32]. To study impacts of the artificial faults on the hysteresis behaviour, DHL of the test samples were measured for the range of magnetisation; the results under sinusoidal induction of 50 Hz and peak flux densities of 1.0 T to 1.7 T are shown in Figs 9-a to 9-d, respectively. Magnetic quantities of the test samples with ILFs are asterisked to distinct them from the inherent properties of the material.

It is evident from Fig 9 that the area surrounded by the DHLs, which measure the total energy loss per unit volume per cycle, is significantly increased by increasing number of the shorted laminations. Additionally, shape of the hysteresis loops is remarkably changed for different types of ILFs. To study impact of the ILFs on magnetising processes, instantaneous waveforms of magnetic field strength $H(t)$ of the test samples for one magnetising cycle under controlled sinusoidal induction of 50 Hz at peak flux densities of 1.0 T to 1.7 T are shown in Figs 10-a to 10-d, respectively.

As a phenomenological impact of ILFs on the hysteresis performance of the magnetic cores, Figs 9 and 10 show that peak magnetic field strength H_m^* is remarkably increased by increasing number of the shorted laminations, which has a direct impact on total energy loss per cycle. In contrast, at each particular flux density, H_b^* of all of the test samples coincide with the peak flux density B_m . This can be interpreted to the effect of ILFs on energy loss components. In the recent study performed by the author [4], it was experimentally proved that ILFs do not affect the hysteresis energy loss. Based on the TSM of (6) and (7), dynamic energy loss of GO steels is directly proportional to dB/dt . At H_b^* , where $dB/dt = 0$, dynamic energy loss component is zero, and the total energy loss is limited to the hysteresis loss only. As a result, the extra energy loss observed in the DHLs is due to the dynamic energy loss component, which is proportional to dB/dt .

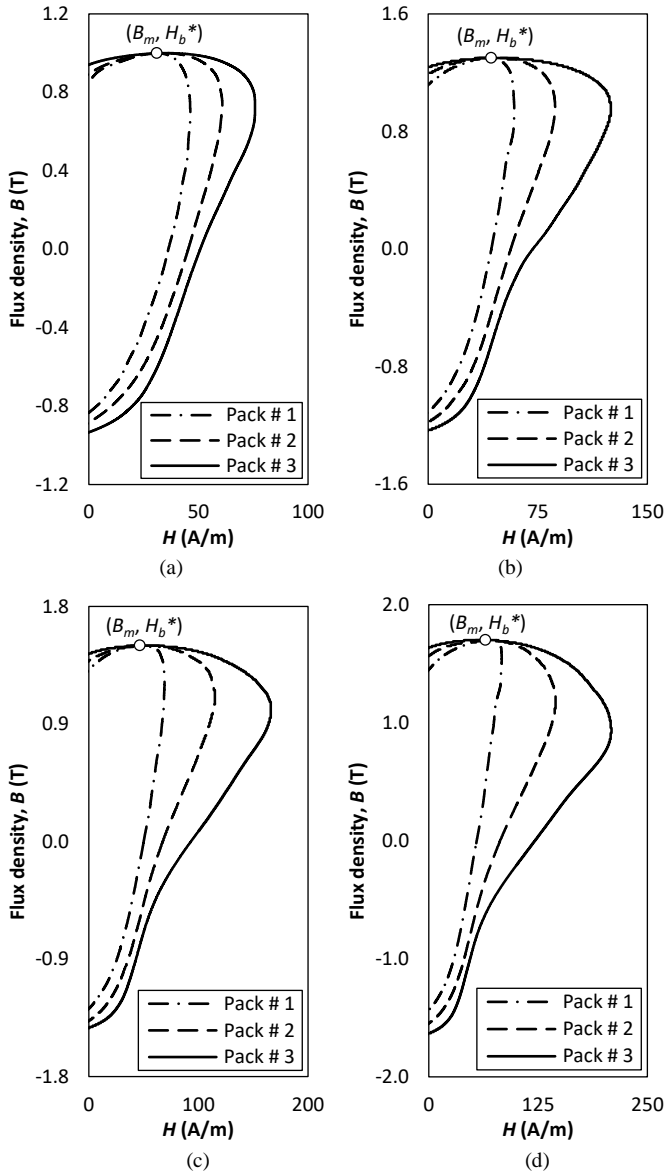


Fig 9 A comparison between the measured DHL of the test samples at magnetising frequency of 50 Hz and peak flux densities of (a) $B_{pk}=1.0$ T (b) $B_{pk}=1.3$ T (c) $B_{pk}=1.5$ T and (d) $B_{pk}=1.7$ T

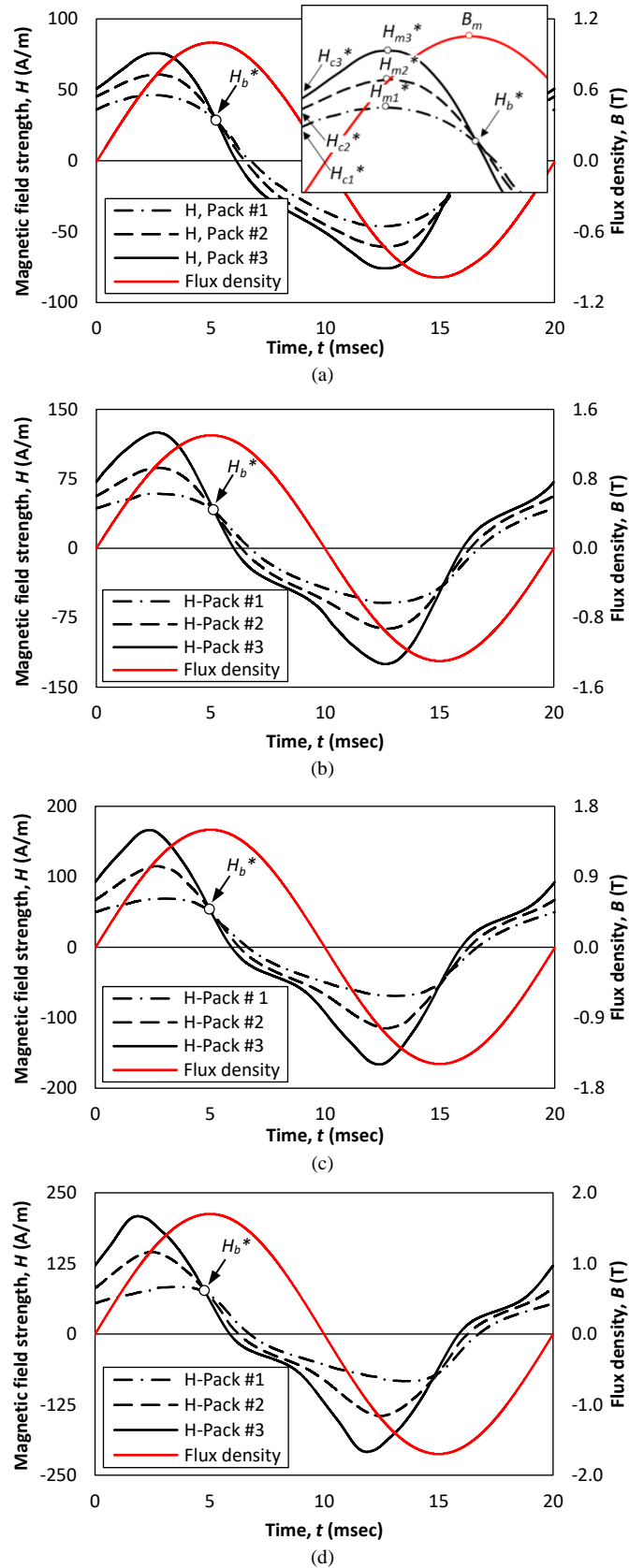


Fig 10 Instantaneous wave shapes of magnetic field strength $H(t)$ of the test samples for one magnetising cycle at frequency of 50 Hz and peak flux densities of (a) $B_{pk}=1.0$ T, (b) $B_{pk}=1.3$ T (c) $B_{pk}=1.5$ T and (d) $B_{pk}=1.7$ T

Phenomenology of the magnetic energy loss can be further interpreted by the general concept of rate-dependent and rate-independent energy loss components of ferromagnetic materials during each cycle of the magnetising processes. Based on the three components loss model (6), hysteresis energy loss is rate-independent, however classical eddy current and excess energy loss components are rate-dependent. The fact that H_m^* is increased by increasing number of the ILFs, and H_b^* is consistent for all types of ILF can be directly interpreted to the dependency of energy loss components on the ILFs. It is well-recognised that ILFs have direct impact on eddy current distribution and hence eddy current loss at the defected zone, which increase the magnetic field associated with the classical eddy current $H_{eddy}(t)$, and hence total magnetic field $H(t)$. On other word, the magnetic hysteresis responds to this defect by widening the loop area, which result in higher energy loss per cycle. Therefore as a phenomenological conclusion on this study, the experimental results of Figs 9 and 10 show that, impacts of ILFs on magnetising processes and magnetic properties of the magnetic cores are purely rate-dependent, which evidently prove the previous conclusion.

Another important note that could be highlighted from this study is impact of the ILFs on the coercive field H_c and residual magnetic field B_r . Generally for any given material, coercive force H_c covers a wide range of magnetic field; in contrast, residual magnetic field B_r has a limited range of flux density [23]. The measured DHLs of Fig 9, and the instantaneous wave shapes of the magnetic field strength $H(t)$ of Fig 10 reflect similar fact, even when the laminations are shorted by the artificial faults. These results indicate that, ILFs do not have a big impact on the residual magnetic field B_r^* of the test samples, but they have a major effect on the coercive field H_c^* . Higher coercive force denotes higher magnetic field to reduce the magnetisation from the residual magnetic field to zero; certainly this is directly linked with the total energy loss per cycle.

C. Relative permeability of the test samples

Magnetic permeability, by definition, is a measure of ability of the materials to sustain an external magnetic field. Magnetic permeability varies with the magnetising regime including magnetising frequency, flux density and level of the applied magnetic field. Magnetic permeability of the electrical steels strongly depends on the grain structure and texture of the material, and hence, it varies by temperature, mechanical stress, manufacturing processes, and other factors which might affect the materials structure. From (1) to (3), at a particular peak flux density B_m and magnetising frequency f , an increase in the peak magnetic field strength H_m reduces the relative permeability of the material. This phenomenon may not be experienced during magnetising processes of a single strip or a magnetic core under normal operation; but it could be the case in the presence of ILF in the core. To study impacts of ILFs on relative permeability, DHL of each test samples at magnetising frequency of 50 Hz and peak flux densities of 1.0 T to 1.7 T, and the corresponding $B_m - H_m^*$ curves are shown in Figs 11-a to 11-c, respectively. Relative permeability of the test samples μ_r^* can be calculated by tracing the $B_m - H_m^*$ curves.

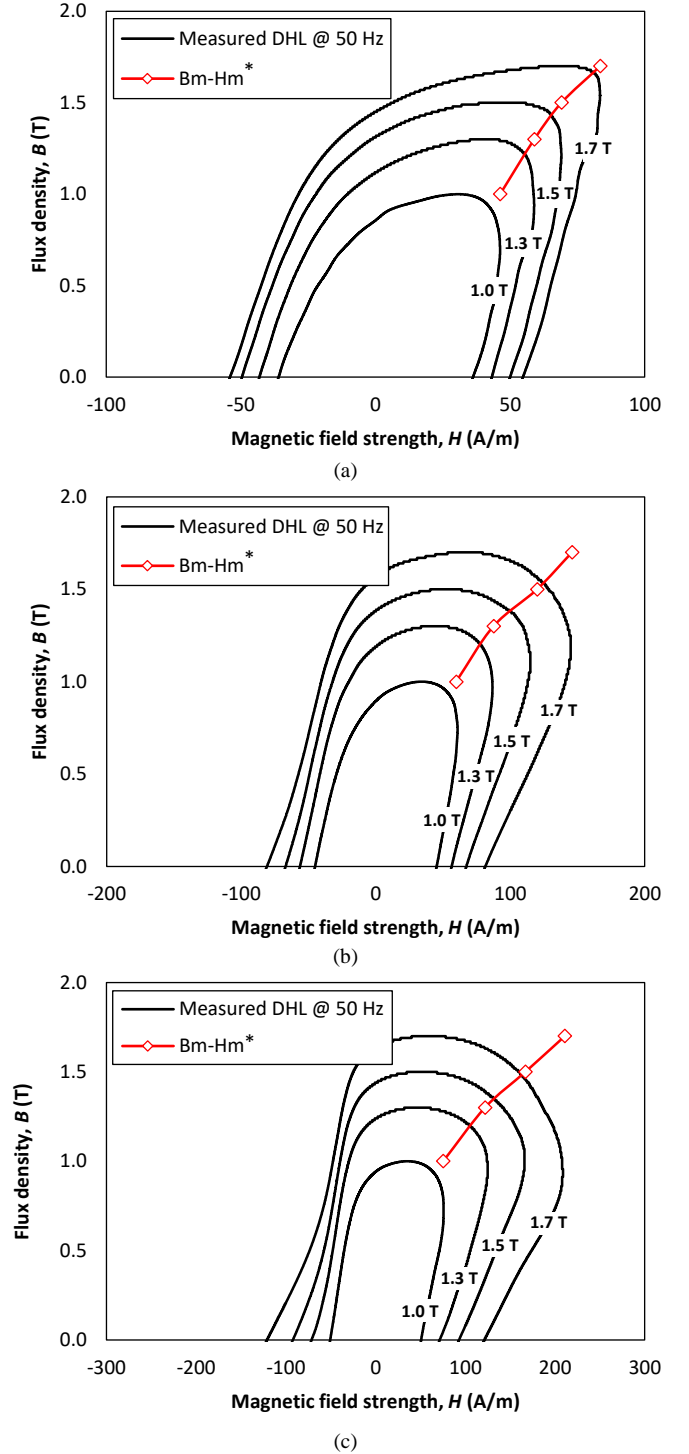


Fig 11 Measured DHL and $B_m - H_m^*$ curves of the test samples at magnetising frequency of 50 Hz and peak flux densities of $B_{pk}=1.0$ T, $B_{pk}=1.3$ T, $B_{pk}=1.5$ T and $B_{pk}=1.7$ T (a) Pack # 1 (b) Pack # 2 (c) Pack # 3

The experiments were then extended to magnetising frequencies up to 1 kHz. Relative permeability of the test samples, as an important quality indicator of the magnetic materials, were calculated from (1) for the whole range of magnetisation. A comparison between the results at magnetising frequencies of 50 Hz to 1 kHz, and peak flux densities of 1.0 T to 1.7 T are shown in Figs 12-a to 12-d, respectively.

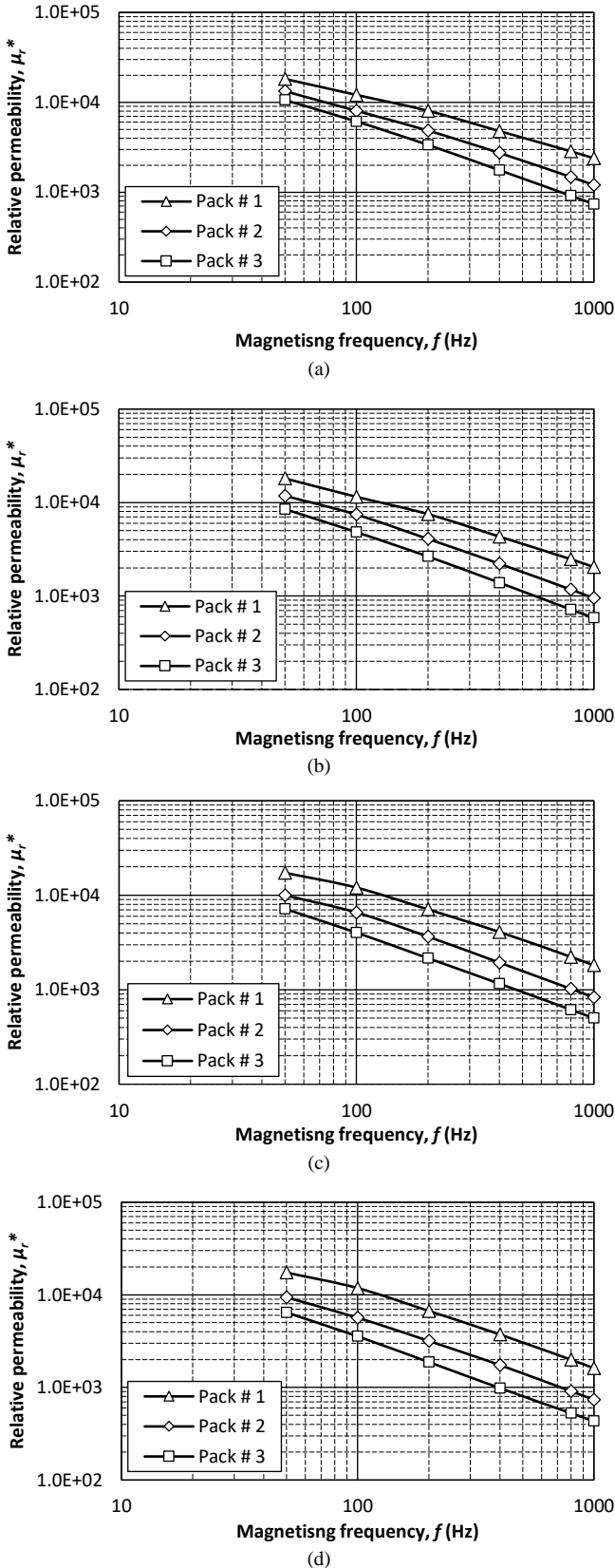


Fig 12 Relative permeability of the test samples versus magnetising frequency for peak flux densities of (a) $B_{pk}=1.0$ T (b) $B_{pk}=1.3$ T (c) $B_{pk}=1.5$ T and (d) $B_{pk}=1.7$ T

Effects of flux density and magnetising frequency on relative permeability of the electrical steels, and other soft magnetic materials, are well understood [23, 33]. However, experimental results of Fig 12 shows that ILFs have significant impact on relative permeability of the magnetic cores, as a result of increased peak magnetic field strength H_m for a given peak flux density B_m . Fig 12 shows that relative permeability of the test samples is significantly declined by increasing number of the shorted laminations, even for low frequency ranges. In fact, this experiment lead to new enlightenment and knowledge regarding the effects of ILFs on quality of the magnetic cores. These results clearly show that ILFs have immediate impact on the relative permeability of the defected zone of the magnetic cores, which directly deteriorate overall quality of the electromagnetic devices. It should be note that, ILFs may not affect inherent properties of the materials, e.g. specific power loss and relative permeability, but they degrade the properties of the defected zone of the magnetic cores.

V. CONCLUSION

With the growing concern about the climate change and its catastrophic impacts on the environment, demand for various types of electromagnetic devices such as electric motors, transformers and reactors has rapidly grown. In this trend, lower power loss and hence higher efficiency components are the key objectives. Higher efficiency levels means significant savings in energy and hence reduction in CO₂ emissions, which bring nationwide benefits for electric companies, manufacturer and state ownership. It is widely recognised that low inter-laminar resistance and inter-laminar short circuit faults, have significant impacts on quality of the magnetic cores of all kinds of electromagnetic devices with laminated cores. Despite the long history of the problem, development of new analytical or practical approaches for quality assessment and condition monitoring of the magnetic cores is still an active research field across the academic and industrial communities.

In this paper a phenomenological approach was proposed to study the impacts of ILFs on the magnetising processes and hysteresis loops of magnetic cores. The proposed approach is based on the dynamic hysteresis behaviour of the test samples according to the reference standard BS EN 10280:2007. Hysteresis phenomenon, as it can observe inherent properties of the materials, is a reliable and accurate approach to characterise magnetic materials and magnetic cores under different magnetising conditions. In this respect, total energy loss W_{tot} , peak flux density B_m , peak magnetic field strength H_m , magnetic field at peak flux density H_b , coercive field H_c , and residual magnetic field B_r are the most important quantities to be considered. The results of this study showed that core quality assessment can be effectively carried out by monitoring the hysteresis loops of the cores, and analysing these quantities. The developed approach offers high accuracy in ILF analysis and can be used in condition monitoring of magnetic cores of real power transformers and other electromagnetic devices with GO material. Although the study was mainly performed on GO steels, but it can be extended to NO steels as it is on the basis of hysteresis phenomenon.

ACKNOWLEDGMENT

The author would like to thank Cogent Power Ltd. for providing the electrical steel strips, and Cardiff University for the experimental data. The author also is grateful to A-Line E.D.S. for providing the images and technical specification of the power transformer shown in Fig 2.

REFERENCES

- [1] A. J. Moses, "Electrical steels: past, present and future developments," IEE Proceedings A - Physical Science, Measurement and Instrumentation, Management and Education, Vol. 137, No. 5, pp. 233-245, Sept. 1990
- [2] P. Beckley, "Electrical Steels for Rotating Machines", Institution of Engineering and Technology, 2002
- [3] Y. Zhang, H. Wang, K. Chen and S. Li, "Comparison of laser and TIG welding of laminated electrical steels", Journal of Materials Processing Technology, Vol. 247, pp 55-63, Sep. 2017
- [4] H. Hamzehbahmani, "An Experimental Approach for Condition Monitoring of Magnetic Cores With Grain-Oriented Electrical Steels," in IEEE Transactions on Instrumentation and Measurement, Vol. 69, No. 6, pp. 3395-3402, June 2020
- [5] H. Hamzehbahmani, P. Anderson, K. Jenkins, and M. Lindenmo, "Experimental Study on Inter-Laminar Short Circuit Faults at Random Positions in Laminated Magnetic Cores", IET Electr. Power App., Vol. 10, Issue 7, pp. 604–613, August 2016
- [6] S. Lee, G. Kliman, M. Shah, D. Kim, T. Mall, K. Nair, and M. Lusted, "Experimental Study of Inter-laminar Core Fault Detection Techniques based on Low Flux Core Excitation" IEEE Trans on Energy Convers, Vol. 21, No. 1, pp 85-94, March 2006
- [7] K. Bourchas, A. Stening, J. Soulard, A. Broddefalk, M. Lindenmo, M. Dahlen and F. Gyllensten, "Quantifying effects of cutting and welding on magnetic properties of electrical steels", IEEE Trans. Ind. Appl., Vol. 53, No. 5, pp. 4269-4278, Sep./Oct. 2017
- [8] H. Weiss, P. Tröber, R. Golle, S. Steentjes, N. Leuning, S. Elfgen, K. Hameyer, and W. Volk "Impact of Punching Parameter Variations on Magnetic Properties of Nongrain-Oriented Electrical Steel", IEEE Trans. on Ind. App., Vol. 54, No. 6, pp. 5869-5878, Nov., Dec. 2018
- [9] C. Ho, D. Bertenshaw, A. Smith, T. Chan, and M. Sasic "Three-dimensional finite element analysis of large electrical machine stator core faults", IET Electr. Power Appl., Vol. 8, No. 2, pp. 60-67, Feb. 2014
- [10] M. Bali and A. Muetze, "Modelling the Effect of Cutting on the Magnetic Properties of Electrical Steel Sheets," in IEEE Transactions on Industrial Electronics, vol. 64, no. 3, pp. 2547-2556, March 2017
- [11] H. Hamzehbahmani, "Development of a New Approach to Core Quality Assessment of Modern Electrical Machines", IET Electric Power Applications, Vol. 13, Issue 6, pp. 750–756, June 2019
- [12] J. Bielawski, S. Duchesne, D. Roger, C. Demian, and T. Belgrand, "Contribution to the Study of Losses Generated by Inter-laminar Short-Circuits", IEEE Trans On Magn, Vol. 48, No. 4, pp 1397-1400, April 2012
- [13] D. Bertenshaw, C. Ho, A. Smith, M. Sasi, and T. Chan, "Electromagnetic modelling and detection of buried stator core faults" IET Electric Power Applications, Vol. 11, Issue 2, pp. 187–196, March 2017
- [14] C. Schulz, S. Duchesne, D. Roger, and J. Vincent, "Short Circuit Current Measurements between Transformer Sheets", IEEE Trans Magn, Vol. 46, No. 2, pp 536-539, Feb 2010
- [15] H. Hamzehbahmani, A. Moses, and F. Anayi, "Opportunities and Precautions in Measurement of Power Loss in Electrical Steel Laminations Using the Initial Rate of Rise of Temperature Method" IEEE Trans. Mag. Vol. 49, No. 3, pp 1264- 1273, March 2013
- [16] R. Mazurek, H. Hamzehbahmani, A. Moses, P. Anderson, F. Anayi, and T. Belgrand, "Effect of Artificial Burrs on Local Power Loss in a Three-Phase Transformer Core" IEEE Trans on Mag. Vol. 48, No. 4, pp 1653-1656, April 2012
- [17] H. Hamzehbahmani, P. Anderson, J. Hall, and D. Fox, "Eddy Current Loss Estimation of Edge Burr Affected Magnetic Laminations Based on Equivalent Electrical Network-Part I Fundamental Concepts", IEEE Trans. on Power Delivery, Vol. 29, No. 2, pp. 642-650, April 2014
- [18] L. Masisi, M. Ibrahim and J. Wanjiku "The Effect of Two- and Three-Level Inverters on the Core Loss of a Synchronous Reluctance Machine

- (SynRM)", IEEE Trans. Ind. Appl., Vol. 52, No. 2, pp. 3805-3813, Sep./Oct. 2016
- [19] D. Bertenshaw, J. Lau, and D. Conley, "Evaluation of EL CID Indications not associated with Stator Core Inter-laminar Insulation Faults" IEEE Electrical Insulation Conference, pp 254- 260, June 2011
- [20] S. Lee, G. Kliman, M. Shah, T. Mall, N. Nair, and R. Lusted, "An advanced technique for detecting inter-laminar stator core faults in large electric machines" IEEE Trans Ind. App., Vol. 41, No. 5, pp.1185–1193, Sep/Oct 2005
- [21] S. Lee, G. Kliman, M. Shah, N. Nair, and R. Lusted, "An iron core probe based inter-laminar core fault detection technique for generator stator cores" IEEE Trans. Energy Conv., Vol. 20, No. 2, pp. 344–351, Jun 2005
- [22] G. Kliman, S. Lee, M. Shah, R. Lusted, and N. Nair, "A new method for synchronous generator core quality evaluation," IEEE Trans. Energy Convers., Vol. 19, NO. 3, pp. 576–582, Sep. 2004
- [23] G. Bertotti, "Hysteresis in Magnetism, For Physicists, Materials Scientists and Engineers", Academic Press 1998
- [24] Z. Cheng, N. Takahashi, B. Forghani, Y. Du, Y. Fan, L. Liu, Z. Zhao, and H. Wang., "Effect of Variation of B-H Properties on Loss and Flux Inside Silicon Steel Lamination," in IEEE Transactions on Magnetism, Vol. 47, No. 5, pp. 1346-1349, May 2011
- [25] G. Bertotti and I. Mayergoyz "The Science of Hysteresis", Academic Press 2005
- [26] S. Zirka, Y. Moroz, N. Chiesa, R. Harrison and H. Høidalen "Implementation of Inverse Hysteresis Model Into EMTP—Part II: Dynamic Model", IEEE Trans On Power Delivery, Vol. 30, No. 5, pp 2233-2241, Oct 2015
- [27] S. Zirka, Y. Moroz, S. Steentjes, K. Hameyer, K. Chwastek, S. Zurek and R. Harrison "Dynamic magnetization models for soft ferromagnetic materials with coarse and fine domain structures", Journal of Magnetism and Magnetic Materials, Vol. 394, pp 229-236, Nov. 2015
- [28] BS EN 10280:2001 + A1:2007, Magnetic Materials - Methods of measurement of the magnetic properties of electrical sheet and strip by means of a single sheet tester, British Standard, 2007
- [29] H. Hamzehbahmani, P. Anderson, and S. Preece, "An application of an Advanced Eddy Current Power Loss Modelling to Electrical Steel in a Wide Range of Magnetising Frequency" IET Science, Measurement & Technology, Vol. 9, Issue 7, pp. 807-816, October 2015
- [30] IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus-Electric Machinery, IEEE Standard 62.2-2004, Jun. 2005
- [31] K. Lee, J. Hong, K. Lee, S. Lee, and E. Wiedenbrug, "A Stator Core Quality Assessment Technique for Inverter-fed Induction Machines", IEEE Industry Applications Society Annual Meeting, pp 1-8, Oct 2008
- [32] H. Hamzehbahmani, "Inter-laminar fault analysis of magnetic cores with grain-oriented electrical steels under harmonic distortion magnetisations," in IET Science, Measurement & Technology, Vol. 14, No. 1, pp. 26-31, January 2020
- [33] H. Hamzehbahmani, P. Anderson and S. Preece, "Application of an advanced eddy-current loss modelling to magnetic properties of electrical steel laminations in a wide range of measurements," in IET Science, Measurement & Technology, Vol. 9, No. 7, pp. 807-816, Oct. 2015

BIOGRAPHY



H. Hamzehbahmani (SM'18) received the B.Eng. degree in electrical engineering from Birjand University, Birjand, Iran, in 2005, the M.Sc. degree in electrical engineering from IUST, Tehran, Iran, in 2007, and the Ph.D. degree in electrical engineering from Cardiff University, Cardiff, U.K., in 2014. He was a Research Associate in the field of earthing systems for high-voltage alternating current (HVAC) and high-voltage direct current (HVDC) systems with Cardiff University. From 2005 to 2008 he worked with various Engineering Consultant companies where he was involved in the field of distribution networks and high voltage substations. From 2016 to 2018, he was a Lecturer in electrical engineering with Ulster University, Londonderry, U.K. He is currently an Assistant Professor in electrical engineering with Durham University, Durham, U.K. His current research interests include magnetic materials and applications, power loss analysis and condition monitoring of transformers and electrical machines, high frequency and transient response analysis of earthing systems, and earthing design of HVDC networks.